U.S. Army
Research Institute of
Environmental Medicine
Natick, Massachusetts

TECHNICAL REPORT NO. T17-02
DATE December 2016
ADA

NOVEL METHOD OF ESTIMATING METABOLIC RATES OF SOLDIERS ENGAGED IN CHEMICAL BIOLOGICAL DEFENSE TRAINING

Approved for Public Release; Distribution Is Unlimited

United States Army
Medical Research & Materiel Command

DISCLAIMER

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25 and SECNAVINST 3900.39D, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

USARIEM TECHNICAL REPORT TR17-02

NOVEL METHOD OF ESTIMATING METABOLIC RATES OF SOLDIERS ENGAGED IN CHEMICAL BIOLOGICAL DEFENSE TRAINING

Alexander P. Welles
William J. Tharion
Adam W. Potter
Mark J. Buller

Biophysics and Biomedical Modeling Division

December 2016

U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
08-12-2016	Technical Report	Aug 2016 - Dec 2016

4. TITLE AND SUBTITLE
NOVEL METHOD OF ESTIMATING METABOLIC RATES OF SOLDIERS ENGAGED IN CHEMICAL BIOLOGICAL DEFENSE TRAINING

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)
Alexander P. Welles
William J. Tharion
Adam W. Potter
Mark J. Buller

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Biophysics and Biomedical Modeling Division
U.S. Army Research Institute of Environmental Medicine
Building 42 - 10 General Greene Avenue
Natick, MA 01760

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and Materiel Command,
Fort Detrick, MD 21702

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Estimates of metabolic rate for typical training exercises during which, chemical, biological, radiological, nuclear, and/or explosive personal protective ensembles are worn are currently unknown. Scientists, materiel developers, and warfighters require these metabolic rates to make informed decisions about the metabolic and thermal effects of working while wearing encapsulating personal protective equipment. Physiological data were collected from volunteers during Chemical Response Team (CRT) and Weapons of Mass Destruction Civil Support Team (WMD-CST) training exercises at three different locations. These data included core temperature (TC) values which were used with contextual environmental and ensemble characteristic data to estimate metabolic rate using the USARIEM developed physics and physiology based thermoregulatory model SCENARIO. Mean metabolic rate values ranged between 184 ± 66 W and 542 ± 142 W and total energy expenditure (EEtot) for each exercise period ranged from 1.2 ± 0.2 MJ to 2.6 ± 0.4 MJ.

15. SUBJECT TERMS
metabolic rate; heat flux; core temperature; metabolic modeling; physiological monitoring; predictive modeling; thermoregulation

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unclassified		Alexander P. Welles
					19b. TELEPHONE NUMBER *(Include area code)* 508-233-5288

Reset

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

Special thanks to the test volunteers from the 22nd Chemical Battalion Technical Escort and the 95th and 1st Weapons of Mass Destruction Civil Support Teams who made this study possible, as well as to the personnel who helped collect data: Alyssa Carter, MAJ David Dominguez, Cynthia Duhamel, Victoria Goetz, Dr. Todd Hughes, Tony Karis, Steven Mullen, CPT Matt Paquin, Jeff Simpson, Dr. Miyo Yokota, and Whitney Young. The authors would also like to thank Dr. Reed Hoyt for editorial comments and scientific guidance.

EXECUTIVE SUMMARY

Estimates of metabolic rate ($\dot{M}$) for typical training exercises during which chemical, biological, radiological, nuclear, and/or explosive (CBRN/CBRNE) personal protective ensembles (PPE) are worn are currently unknown. Scientists, materiel developers, and warfighters require these $\dot{M}$ to make informed decisions about the metabolic and thermal effects of working while wearing encapsulating PPE. In particular, knowing these metabolic costs can help guide the development of PPE and equipment by materiel developers as well as maximize warfighter training safety. Physiological data were collected from volunteers during Chemical Response Team (CRT) and Weapons of Mass Destruction Civil Support Team (WMD-CST) training exercises at three different locations: Edgewood, MD; Hayward, CA; and Hanscom Air Force Base, MA. These data included core temperature (T_C) values which were used with contextual environmental and ensemble characteristic data to estimate $\dot{M}$ using the USARIEM developed physics and physiology based thermoregulatory model SCENARIO [5,13].

Heart rate (HR), T_C, and skin temperature (T_S) data were collected from a total of 25 test volunteers using the chest-worn physiological status monitoring system (PSM) (EQ-02 Hidalgo Ltd., Cambridge, UK) during 2 to 3 days of training exercises per site location. Exercises occurred indoors and outdoors and volunteers wore either the Joint Service Lightweight Integrated Suit Technology (JSLIST) in Mission Oriented Protective Posture IV (suit, mask, boots, gloves; MOPP 4) or Level A CNRNE-PPE. Air temperature (T_A) and relative humidity (RH) values ranged from 14.6 to 18.7°C and 36 to 85% respectively.

The low vapor permeability and high insulation characteristics of the CBRN/CBRNE-PPE worn during these training exercises resulted in measured mean maximum core temperature increases ($\Delta T_{C,max}$) of up to 1.7°C during training periods of 1 to 2 hours depending primarily on the work rates associated with the training activity. To estimate $\dot{M}$ profiles capable of generating the observed $\Delta T_{C,max}$ values, observed T_C and environmental (T_A, RH) values were used as inputs to the SCENARIO thermoregulatory model and a $\dot{M}$ was generated for each volunteer. Volunteer data were then binned into one of three work intensity groups depending on work intensity as defined by Sawka and Pandolf, 2001 [11]: “light” where $\dot{M}$ < 300 W, “moderate” where 300 W ≤ $\dot{M}$ < 450 W, and “high” where $\dot{M}$ ≥ 450 W. Mean $\dot{M}$ values ranged between 184 ± 66 W and 542 ± 142 W and total energy expenditure (EE_{tot}) for each exercise period ranged from 1.2 ± 0.2 MJ to 2.6 ± 0.4 MJ. The metabolic profiles are presented in graphical formats.

INTRODUCTION

Warfighters and law enforcement professionals must often wear bulky and encapsulating personal protective equipment (PPE) to prevent injury from or exposure to chemical, biological, radiological, nuclear, and/or explosive hazards (CBRN and CBRNE where CBRN refers specifically to equipment without explosive protection, CBRNE refers to CBRN equipment with explosive protection such as body armor, and CBRN/E refers to both types of PPE at once). However, wearing these PPE ensembles comes at the cost of reduced capacity for thermoregulation due to their extremely low vapor permeability and high insulation [8]. In addition, CBRN and CBRNE-PPE ensembles often include bulky or heavy equipment such as self-contained breathing apparatuses (SCBA) and body armor which increase metabolic rate ($\dot{M}$) and thermogenesis due to load carriage. It has also been reported that wearing these protective ensembles is associated with increased metabolic costs beyond simple load carriage, e.g., due to restricted or awkward movements [3]. Reduced heat dissipation capacity and increased $\dot{M}$ demands while wearing CBRN and CBRNE-PPE can lead to rapid increases in skin and core temperature (T_C) over short time periods as well as increased risk of heat exhaustion, syncope, and possible heat stroke.

The U.S. Army has developed guidelines to mitigate the potential for rapid T_C increases when operating in CBRN and CBRNE by adjusting physical activity levels as a function of the Wet-Bulb Globe Temperature (WBGT) index [12]. However, these adjustments (adding 5, 10, and 20°C to the WBGT index depending on level/type of PPE, work rate, and humidity) provide only gross estimates of what activities are acceptable for a given set of environmental conditions by binning activities such as walking on hard surfaces while carrying loads and patrolling into “light,” “moderate,” and “hard” work. Previously the energy expenditure of tactical law enforcement personnel has been estimated using the factorial method [4]. However, this method requires task-by-task observations and is not suitable for non-research applications. Estimating the work rates of CBRN/E operations and tasks is also unlikely to be straight forward as actual missions can encompass a wide range of activities and work rates (e.g., site sampling and surveying versus approach marches and multi-story casualty evacuations). Estimating $\dot{M}$ for such a wide range of activities is difficult as even the simplest and most sedentary activities can be made more difficult and metabolically costly by encapsulation and ensemble load.

Cooling systems have been developed for use within CBRN/E ensembles in an effort to increase operational time while mitigating the chances of thermal injury. Power requirements can be prohibitive as these devices require the wearer to carry a power source (e.g., battery). Therefore, the goal of the use of such a system is to determine the necessary cooling schedule given the thermal strain the user is experiencing to guarantee their safety (and not necessarily comfort). Determining an effective rate or schedule for cooling by such apparatuses is a difficult task dependent on not only environmental conditions and ensemble configuration but also the rate at which heat is being generated in the individual by thermogenesis (i.e., due to muscular activity and proportional to $\dot{M}$). Thus, determining $\dot{M}$ of personnel during CBRN/E operations is key as it is a necessary input for mitigating thermal-work strain by either the use of environmental guidelines or personal cooling devices.

Although there are several gold standard methods of measuring or estimating $\dot{M}$, they are largely impractical given CBRN/E training activities and environments. For example: the measurement of oxygen consumption via a face-mask can be impeded by the use of a rebreather or similar CBRN device, whole room calorimeters limit the type of training activity and number of volunteers and require a dedicated and controlled room/chamber [7], doubly labeled water provides only daily energy expenditures, and analysis of accelerometry signals can be confounded by high loads and non-locomotion activities (e.g., climbing) [7]. As noted above, estimating $\dot{M}$ via the factorial method has been effective [4] but, requires detailed records of activity type and duration [7]. However, another option exists for estimating $\dot{M}$ when personnel are instrumented with physiological status monitoring (PSM) systems capable of collecting T_C. In this case, $\dot{M}$ can be estimated using a human thermoregulatory model and verified with T_C values observed during training exercises.

This study estimated the metabolic cost profiles associated with various CBRN/E training exercises. Observed T_C profiles of volunteers at three different training sites over the course of two to three days at each site are presented. Metabolic profiles and total energy expenditure for each period are estimated using the thermoregulatory model, SCENARIO [5,13,14].

METHODS

VOLUNTEERS

Core temperature and environmental data were collected during U.S. Army Chemical Response Team (CRT) and Weapons of Mass Destruction-Civil Support Teams (WMD-CST) CBRN/E training activities at three different locations. A total of 27 Soldier volunteers (25 male, 2 female, age = 29.9 ± 6.4 yr (± standard deviation), height = 1.77 m, body mass = 82.5 ± 13.3 kg, body fat = 18.5 ± 7.4%) participated in regularly scheduled training activities. Volunteers had previously worn CBRN/E-PPE (Figure 1) and had been training with their respective units for at least two years.

All volunteers were briefed on the purpose, risks, and benefits of the study and provided written informed consent prior to their participation. The investigators adhered to the policies for protection of human volunteers as prescribed in Army Regulation 70-25 and SECNAVINST 3900.39D as well as adhering to the provisions of 32 CFR Part 219.

TRAINING ACTIVITIES

Edgewood, MD

Twelve U.S. Army 22nd Chemical Battalion Technical Escort (TE) CRT Soldiers participated in two days of indoor training exercises within a large warehouse without air conditioning (Day 1: air temperature, T_A = 28.7°C, relative humidity (RH) = 67%; Day 2: T_A = 28.1°C, RH = 69%). Data presented are from the 7 of the 12 volunteers who donned PPE and were monitored on both days. Volunteers wore the Joint Service Lightweight Integrated Suit Technology (JSLIST) uniform, rubber boots, protective mask (M40, M50, or M52) in Mission Oriented Protective Posture IV (suit, mask, boots, gloves; MOPP 4) (see Clothing and Equipment Characteristics section, Figure 1, left panel). Three of the volunteers were part of an Explosive Ordinance Disposal (EOD) team and wore Improved Outer Tactical Vests (IOTVs) and Kevlar Helmets in addition to their JSLIST MOPP 4 ensembles. Training exercises lasted approximately 75 minutes with 45 minutes of full encapsulation.

Day 1 and 2: Explosive Device Disarmament and Site Sampling

Training was similar for both days during which volunteers in the EOD team (n = 3) donned their PPE, walked 10 m into a set of rooms within the warehouse, and searched for and disarmed simulated explosive devices. Members of the CRT team in CBRN-PPE (n = 4) approached and entered the warehouse after the EOD team completed disarming the simulated explosive devices and began searching for simulated CBRN material samples which they analyzed and collected on site. Both EOD and CRT teams exited the simulated threat rooms and traveled ~20 m (within the warehouse) before being decontaminated by the decontamination team (n = 4).

Hayward, CA

Eight U.S. Army National Guard Soldiers participated in three days of training exercises in Hayward, CA. All volunteers wore Level A CBRN-PPE.

Day 1: Approach March

Eight volunteers walked for approximately 45 minutes in Level A CBRN-PPE including a SCBA (Clothing and Equipment Characteristics section, Figure 1, right panel). Volunteers walked at their own pace covering approximately 2 km outdoors (T_A = 21.9°C, RH = 36%) in direct morning sunlight without cloud cover.

Day 2: Site Survey, Documentation, and Sample Collection

Six volunteers walked approximately 100 m to an indoor simulated illicit drug laboratory (T_A = 14.6°C, RH = 79%) where they documented and photographed the site and collected material samples. Once documentation and sampling was complete (~60 minutes) the volunteers exited the laboratory and underwent decontamination. Most of the training took place within a non-air conditioned building with windows and doors open to the outside during the morning (T_A = 14.6°C, RH = 79%).

Day 3: Site Survey and Casualty Retrieval

Six volunteers walked approximately 400 meters to a fire tower where they performed a site survey. The tower was not air conditioned but the windows and doors were open to the outside during the morning training (T_A = 16.0°C, RH = 48.5%). Training activities included surveying the tower (ascending four flights of stairs), clearing each room, and upon discovery, evacuating a simulated casualty (~85 kg manikin). The casualty was evacuated via sked down four flights of stairs and to the decontamination line.

<u>Hanscom Air Force Base, MA</u>

Seven U.S. Army National Guard WMD-CST Soldiers wore Level A CBRNE-PPE during two days of outdoor and indoor training exercises (Day 1: air temperature, T_A = 18.1°C, relative humidity (RH) = 43%; Day 2: T_A = 17.7°C, RH = 85%). Of the 7 participating volunteers, 5 used SCBA and 2 used powered air-purifying respirator systems. Training exercises were less than 60 minutes long and were repeated on the second day.

<u>Days 1 and 2: Berm Construction, Site Survey and Sampling, and Casualty Evacuation</u>

All volunteers walked about 25 meters to the entrance of the indoor training facility. Within the building, 2 volunteers constructed a subway track berm designed to collect runoff decontamination liquids used to clean subway tracks. Construction of the berm required carrying 23 kg containers. The remaining 5 volunteers engaged in indoor site survey and material sampling in a simulated chemical laboratory. Specific activities included evacuating a simulated casualty (~85 kg manikin) by sked, taking chemical and glass-ware inventory, and assembly/reassembly of chemical and glassware equipment (cognitive and fine motor tasks). These activities required repeated trips up and down a three story staircase.

CLOTHING AND EQUIPMENT CHARACTERISTICS

Total clothing insulation ($I_{tot,clo}$) and water vapor permeability index (i_m) values were used as model inputs to account for the thermal properties of the ensembles volunteers wore. A clo is a unit of thermal resistance defined as the insulation required to keep a resting human comfortable at 21°C [1]. A clo value of 1 is equal to 0.155 K•m^2/W [1] and roughly equivalent to wearing an ensemble including men's underwear briefs, khaki pants, belt, socks, athletic shoes, and a short-sleeved shirt ($I_{tot,clo}$ = 1.17 clo) [1].The permeability index is a non-dimensional index from 0 to 1 where 0 indicates a garment or ensemble is impermeable to vapor transfer and does not allow evaporative vapor/heat transfer. An i_m of 1 indicates the theoretical maximum of evaporative heat loss given the worn ensemble's insulation [2]. The ratio of $i_m/I_{tot,clo}$ indicates the "cooling power" of an ensemble [2].

Total clo and i_m for the JSLIST MOPP 4 ensemble (Figure 1, left) were input as reported by Potter et al. (2015) (2.248 clo and i_m value of 0.387 at 1 m/s wind velocity) [9]. However, ensemble insulation and permeability characteristics are not currently known for the Level A ensemble. They were assumed to be similar to the Tychem ™

ensemble for protection against the Ebola virus described by Potter et al. (2015) due to the high degree of impermeability and use for protection against a biological agent (1.41 clo and i_m of 0.0846 at 1 m/s wind velocity) [10]. Typical configurations of the MOPP4 JSLISTand Level A ensembles are shown in Figure 1 below (left panel MOPP4, right panel Level A). Individuals encapsulated in the Level A CBRNE-PPE wore SCBAs under the outer protective shell.

Figure 1: Typical ensemble configurations for Joint Service Lightweight Integrated Suit Technology (JSLIST) Mission Oriented Protective Posture IV (MOPP 4, left panel) and Level A Chemical Biological Radiological Nuclear ensembles (right).

ENVIRONMENTAL CONDITIONS

Air temperature (T_A) and relative humidity (RH) were collected using a Campbell Scientific Inc. (Logan, UT), CR-10X weather station for outdoor data collection and up to 16 HOBO Pro v2 temperature and relative humidity loggers (Onset Computer Corporation, Pocasset, MA) in any enclosed/indoor locations.

PHYSIOLOGICAL MEASURES

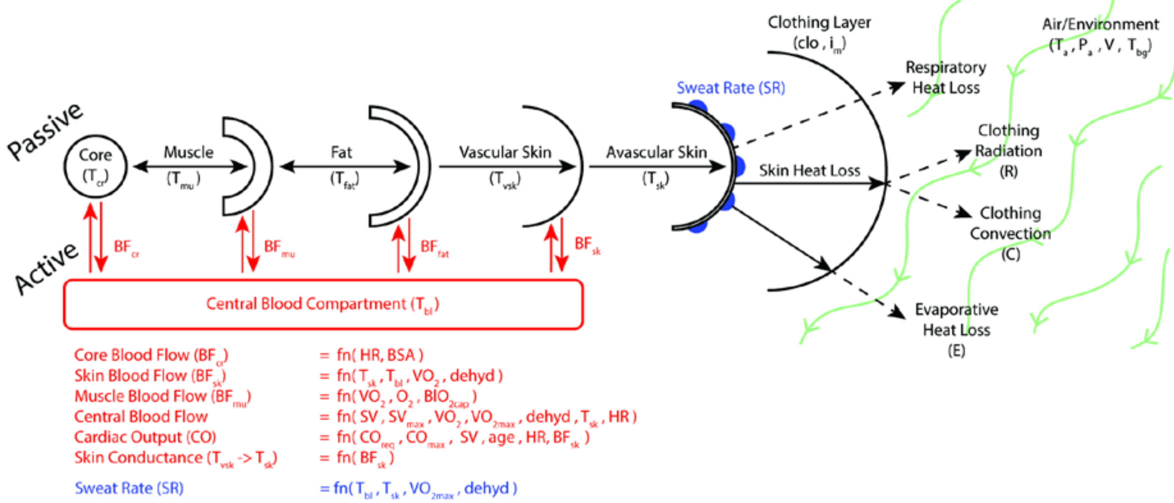
Prior to beginning any training event, volunteers were fitted with and donned a chest belt PSM system (EQ-02, Hidalgo Ltd., Cambridge, UK) and ingested a thermometer pill (Jonah ^{TM}Core temperature Pill; Respironics; Bend, OR) at least 12 hours prior to the training event and on the morning of the event. The PSM systems recorded heart rate (HR, derived from electrocardiogram waveform) respiration rate (RR, derived from chest expansion/contraction), activity counts (AC, derived from triaxial accelerometer), skin temperature (T_{sk}, thermistor), and core temperature (T_C, ingested thermometer pill) at 15 second intervals.

Participant data were broken up by training location and day as well as mean estimated $\dot{M}$ for day. The categories were: “light” work intensity for mean $\dot{M}$ less than or equal to 300 W, “moderate” for mean $\dot{M}$ values greater than 300 W and less than or equal to 450 W, and “high” for $\dot{M}$ values greater than 450 W. These categories were chosen based on definitions of light, moderate, and high work rate given for various military activities by Sawka and Pandolf, 2001 [11]. Data were excluded from one volunteer due to erroneously low core temperature values due to ingestion of water (Hayward, Day 3, n = 1). In these cases the pill from the previous evening was passed and a new pill had to be administered the day of data collection, thus the susceptibility to changes in temperature from drinking water.

METABOLIC RATE ESTIMATION USING THERMOREGULATORY MODEL

The SCENARIO thermoregulatory model [5,13] predicts T_C given a number of inputs in addition to $\dot{M}$, including: environmental parameters (T_A; black globe temperature, T_{BG}; windspeed, WS; and RH), worn ensemble characteristics (i_m, $I_{tot,clo}$), and individual anthropometrics (height, body mass, % body fat). Time series inputs such as environmental conditions and $\dot{M}$ are input in minute time-steps. The SCENARIO model is comprised of a set of active and passive components each responsible for modeling the exchange of heat through the human body by physical or physiological means. The passive components of the model simulate the human as a series of six concentric cylinders where the outer 5 represent various tissue types (muscle, fat, vascular skin, avascular skin) while the innermost is the core viscera. The active components are made up of a combination of equations and algorithms that control blood flow through each of the passive components (except avascular skin). A general overview of the model is shown below in Figure 2.

Figure 2: The passive physical components and active physiological components of the SCENARIO thermoregulatory model.



Note that in Figure 2, active component abbreviations (red or blue) include: blood flow (BF), blood oxygen capacity (BIO_{2cap}), body surface area (BSA), cardiac output (CO), dehydration level (dehyd), stroke volume (SV), and oxygen uptake volume (VO_2). The passive component (in black) subscripts cr, mu, fat, vsk, and sk refer to the cylinders modeling core, muscle, fat, vascular skin, and avascular skin respectively.

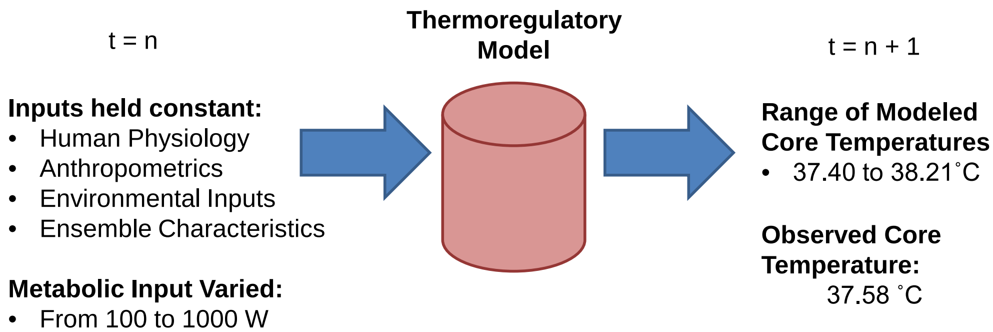
Metabolic rate was estimated by generating a range of estimated T_C values using SCENARIO and comparing the T_C estimates to observed values for each volunteer. Generating the range of estimated T_C values was done by holding all SCENARIO inputs constant while inputting a range of $\dot{M}$ for each time-step (e.g., 1 minute). The minimum value for $\dot{M}$ was determined by calculating resting $\dot{M}$ ($\dot{M}_{rst}$) using Mifflin et al. [6] (equation 1):

$$\dot{M}_{rst} = (10 \bullet BW + 6.25 \bullet HT - 5 \bullet age + 5) \bullet \frac{4184}{24 \bullet 60^2} \qquad (1)$$

where BW is body weight in kilograms, HT is height in centimeters, age is in years, and the fraction at the end converts between kilocalories and watts (Js^{-1}). The calculated $\dot{M}_{rst}$ value was then rounded up to the nearest whole number. The maximum $\dot{M}$ value selected was 1000 W as this rate was deemed likely to exceed the true $\dot{M}$ for all volunteers and all days.

Once the range of $\dot{M}$ and other inputs had been passed into SCENARIO and a range of estimated T_C values had been generated, the root square error (RSE) between each estimated T_C value and the observed value were calculated. The $\dot{M}$ that produced the estimated T_C value with the lowest RSE was then selected as the best input for that time-step (t = n) and the procedure was repeated for the next time-step (t = n + 1, Figure 3).

Figure 3: Simplified example of estimating metabolic rate from core temperature using the SCENARIO thermoregulatory model.



	Metabolic Rate (W)	Modeled Core Temperature (˚C)	RSE	
	273	37.54	0.04	
	274	37.56	0.02	
Selected Input	275	37.58	0.00	Lowest Error
	276	37.60	0.02	
	277	37.62	0.04	
	278	37.64	0.06	

Although the model takes inputs in minute time-steps, $\dot{M}$ values can be entered in time-step bins of any length. For example, the same $\dot{M}$ value can be specified for 5 minutes at a time. The process remains the same with the exception that RMSE for each time-step bin is calculated rather than the RSE. In Figure 3 this would translate to the RSE column being replaced with an RMSE column and the time-step value n indicating the bin number rather than the minute number.

The use of time-step bins is an improvement as previously larger $\dot{M}$ time-step input bins resulted in fewer changes in estimated $\dot{M}$ values translating to a "smoother" $\dot{M}$ profile but at the cost of potentially greater error [14]. This was in part due to a first order lag equation built into SCENARIO to prevent rapid and non-physiological changes in values such as heart rate and blood flow [5]. However, if the first order lags are disabled much smaller time-step bins of 5 minutes (versus 15-25 minute bins) can be used. Five minute bins were selected as they result in the lowest RMSE errors between observed and estimated T_C for the entire dataset.

RESULTS

ENVIRONMENTAL CONDITIONS

Table 1 shows observed air temperature (T_A) and relative humidity (RH) for each training location and day. Indoor black globe temperature (T_{BG}) and wind speed were estimated as equal to T_A and 0.4 m/s respectively. In the case of direct morning sunlight, T_{BG} was estimated as T_A + 5°C.

Table 1: Mean observed environmental conditions for each training location and training period.

Location	Day	Air Temperature (°C)	Relative Humidity (%)
Edgewood	1	28.7	67.2
	2	28.1	68.9
Hayward	1	21.9	36.2
	2	14.6	79.3
	3	16.0	48.5
Hanscom	1	18.1	42.9
	2	17.7	84.7

PHYSIOLOGICAL MEASURES

Table 2 and Figures 4 through 18 present observed and estimated T_C as well as mean estimated $\dot{M}$ data by location, day, and work rate bin (mean ± standard deviation, when number of subjects is greater than 1). Figure 19 presents a single volunteer's $\dot{M}$ profile for the Hayward location on Day 3.

Table 2: Mean (± standard deviation) observed (Obs) core temperature (T_C) and maximum core temperature change ($\Delta T_{C,max}$), estimated (Est) metabolic rate ($\dot{M}$) and total Energy Expenditure (EE_{tot}), and root mean square error between observed and estimated core temperature values for each training event by location, day, and work intensity bin.

Location	Day	Work Intensity	Num. of Sub.	Obs. T_C (°C)	Est. T_C (°C)	Obs. v. Mod. T_C (°C)	$\Delta T_{C,max}$ (°C)	Est. $\dot{M}$ (W)	Est. EE_{tot} (MJ)
Edgewood	1	Light	11	37.4 ± 0.2	37.4 ± 0.2	0.06 ± 0.05	0.8 ± 0.4	225 ± 57	1.7 ± 0.3
		Moderate	1*	38.2	38.2	0.02	0.7	328	1.9
		High	0	-	-	-	-	-	-
	2	Light	4	37.3 ± 0.2	37.4 ± 0.2	0.10 ± 0.10	1.0 ± 0.4	223 ± 143	1.8 ± 0.5
		Moderate	2	37.9 ± 0.5	37.9 ± 0.4	0.05 ± 0.02	1.7 ± 0.5	319 ± 177	2.4 ±0.5
		High	0	-	-	-	-	-	-
Hayward	1	Light	3	37.1 ± 0.4	37.2 ± 0.3	0.12 ± 0.04	1.2 ± 0.5	247 ± 178	1.5 ± 0.1
		Moderate	1*	37.3	37.4	0.08	1.1	301	1.5
		High	3	37.9 ± 0.5	37.9 ± 0.5	0.03 ± 0.02	1.6 ± 0.2	515 ± 178	2.5 ± 0.1
	2	Light	6	37.3 ± 0.1	37.3 ± 0.1	0.08 ± 0.07	0.4 ± 0.1	184 ± 66	1.3 ± 0.2
		Moderate	0	-	-	-	-	-	-
		High	0	-	-	-	-	-	-
	3	Light	6	37.2 ± 0.1	37.3 ± 0.1	0.08 ± 0.10	0.5 ± 0.5	217 ± 140	1.2 ± 0.3
		Moderate	0	-	-	-	-	-	-
		High	0	-	-	-	-	-	-
Hanscom	1	Light	3	37.3 ± 0.2	37.4 ± 0.2	0.13 ± 0.01	0.8 ± 0.1	260 ± 175	1.3 ± 0.1
		Moderate	2	37.5 ± 0.3	37.5 ± 0.3	0.08 ± 0.08	1.0 ± 0.3	363 ± 266	1.8 ± 0.2
		High	2	38.3 ± 0.3	38.3 ± 0.3	0.01 ± 0.01	0.9 ± 0.8	542 ± 142	2.6 ± 0.4
	2	Light	2	37.2 ± 0.2	37.3 ± 0.2	0.13 ± 0.06	0.6 ± 0.3	232 ± 158	1.2 ± 0.2
		Moderate	3	37.6 ± 0.3	37.6 ± 0.3	0.04 ± 0.02	1.0 ± 0.1	392 ± 231	2.0 ± 0.3
		High	2	37.9 ± 0.2	37.9 ± 0.2	0.02 ± 0.00	0.6 ± 0.4	494 ± 149	2.2 ± 0.1

*Denotes a single subject where no standard deviation is reported and mean values are for that subject's data over time.
RMSE ± SD calculated between observed and estimated core temperature only.
Work intensity is binned as "light": $\dot{M}$ < 300 W, "moderate": 300 W ≤ $\dot{M}$< 450 W, "high": $\dot{M}$ ≥ 450 W.
SD = standard deviation of mean values across volunteers.
MJ = Megajoules.

Figure 4: Edgewood training site, Day 1, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

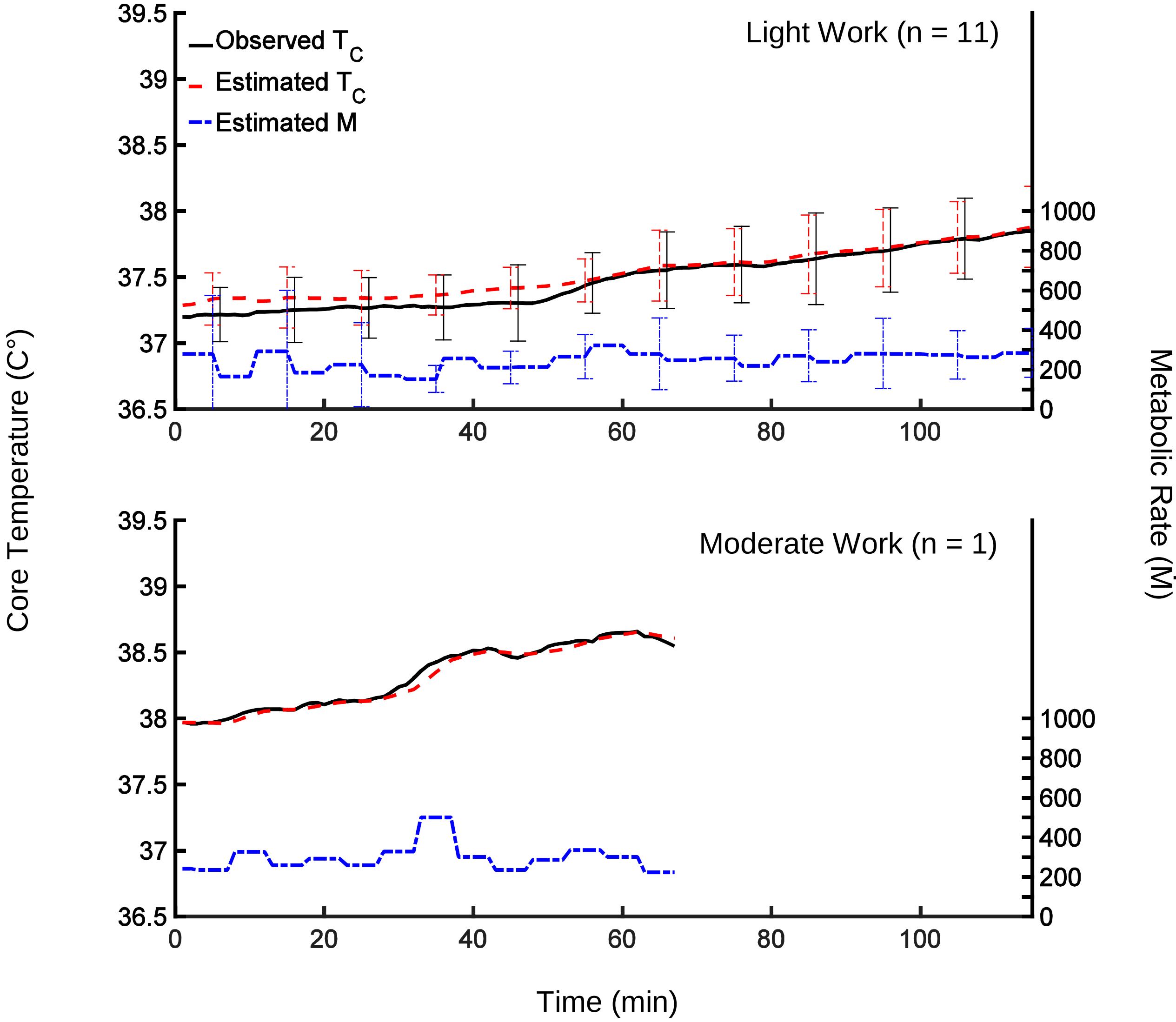


Figure 5: Edgewood training site, Day 2, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

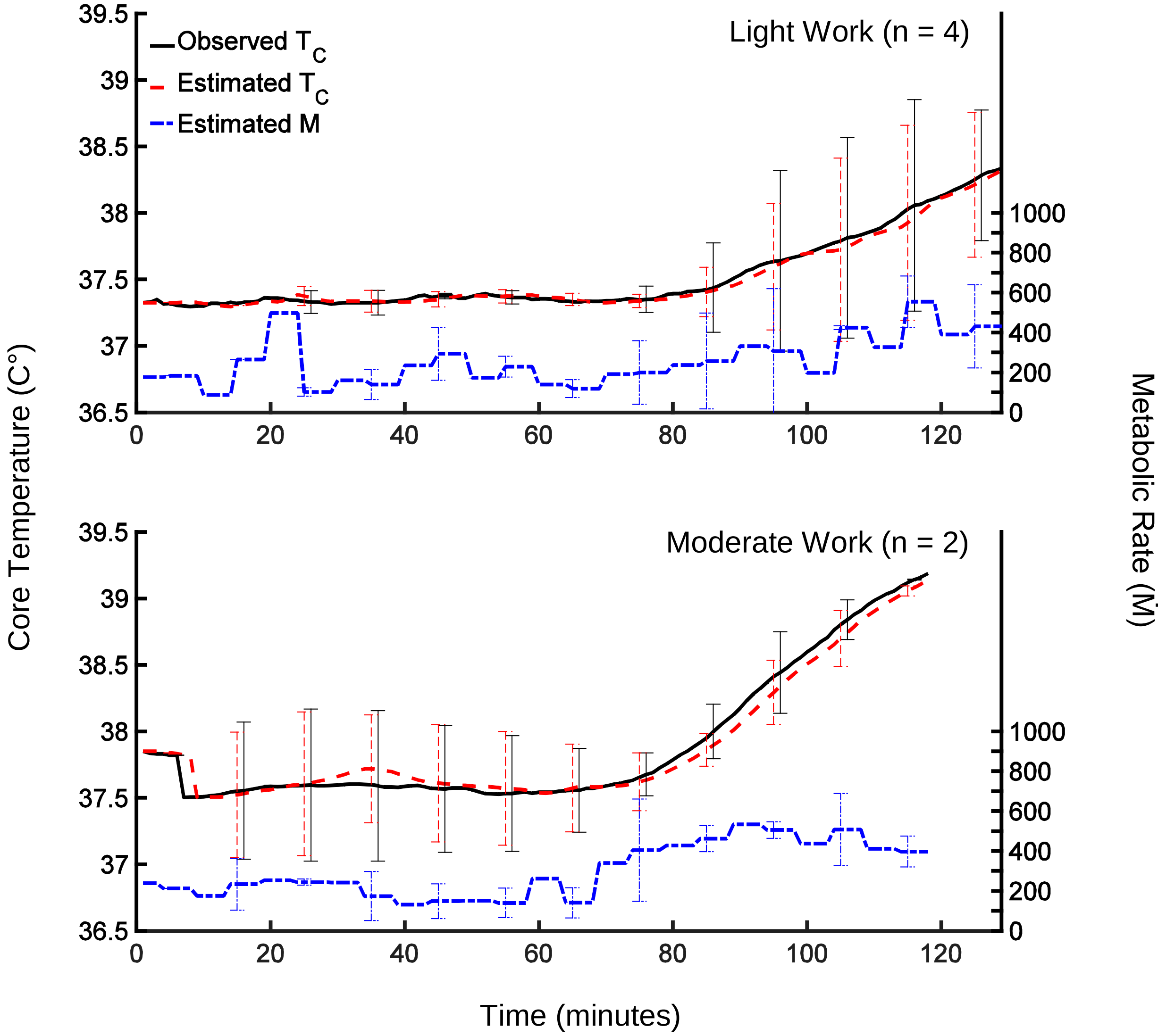


Figure 6: Hayward training site, Day 1, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

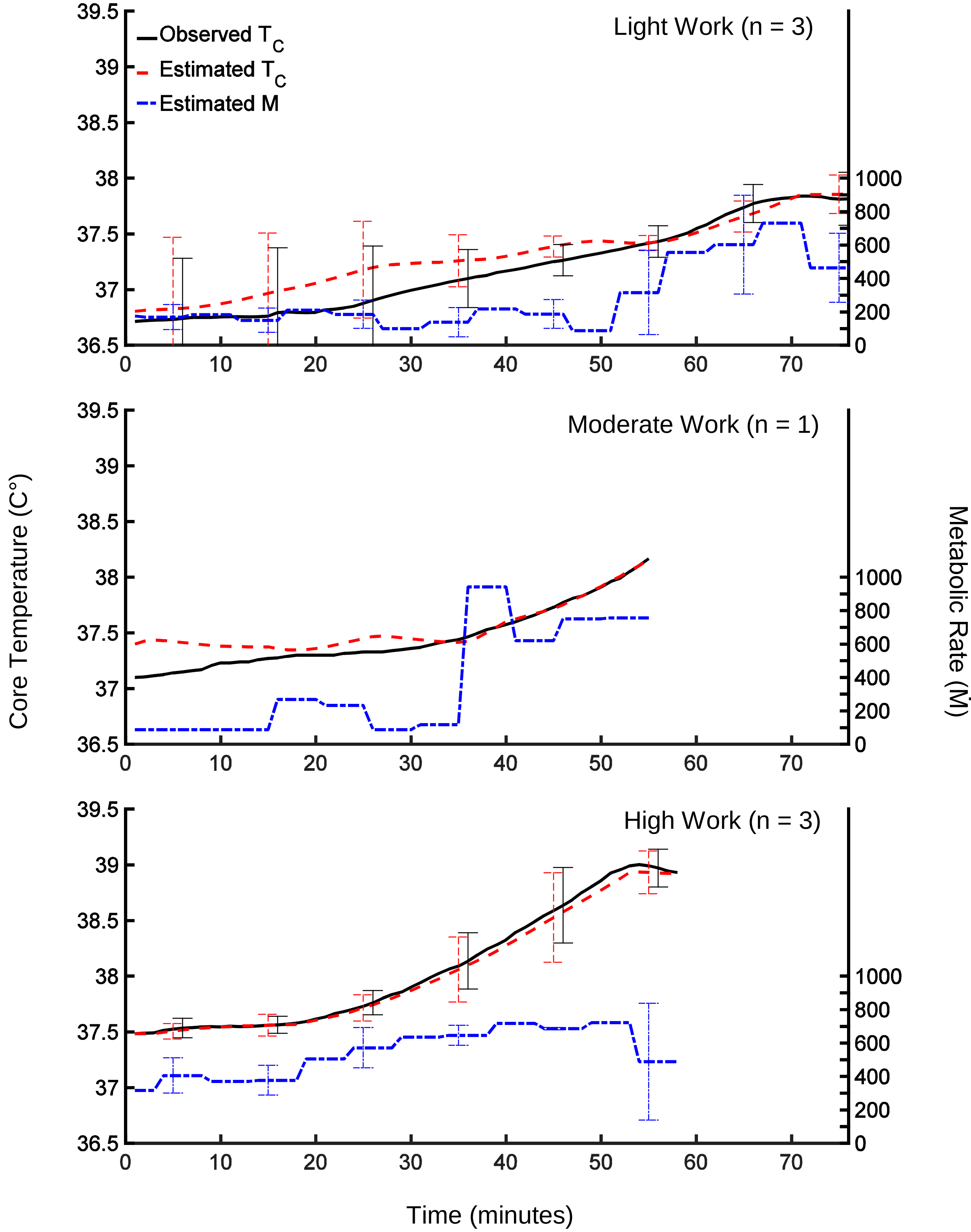


Figure 7: Hayward training site, Day 2, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

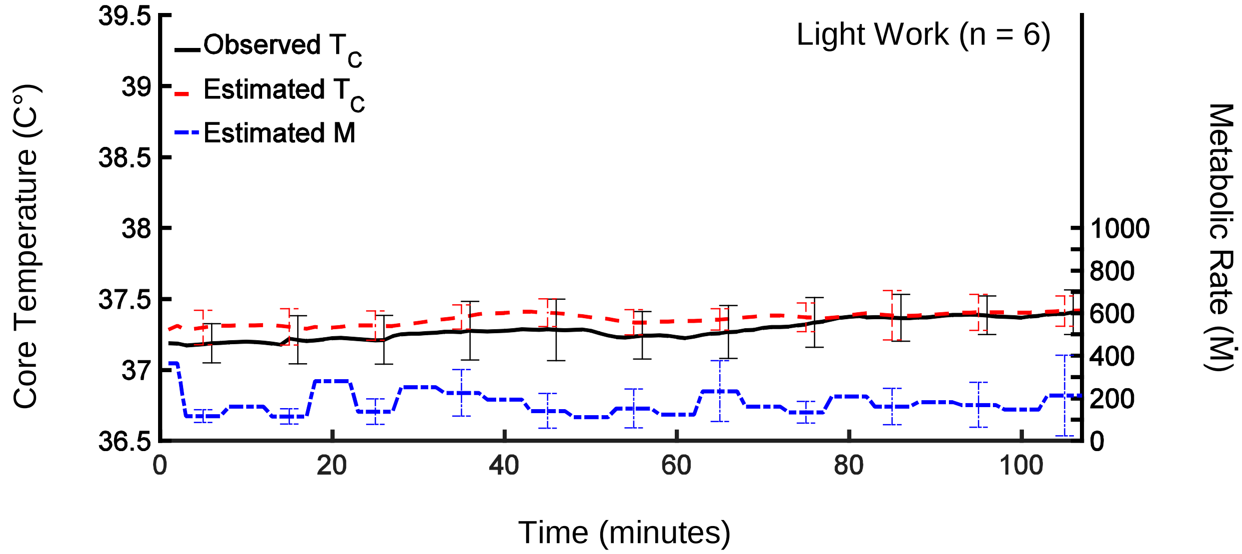


Figure 8: Hayward training site, Day 3, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

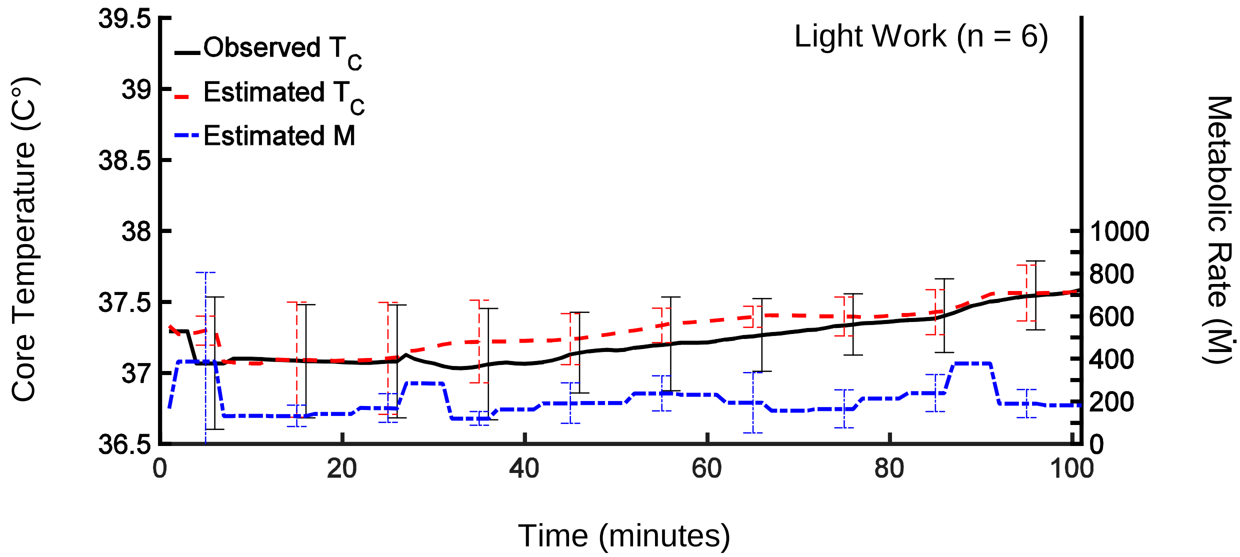


Figure 9: Hanscom training site, Day 1, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

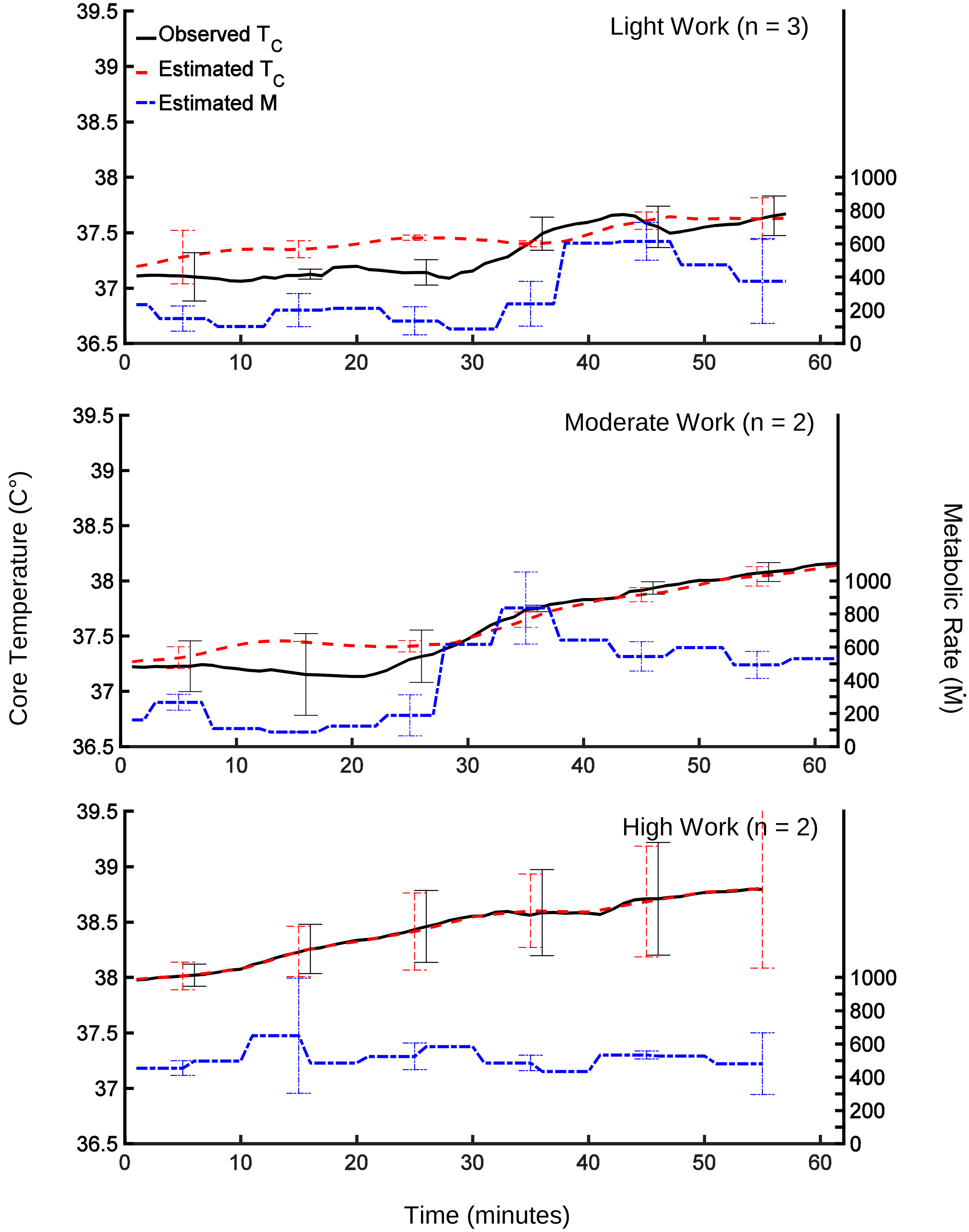


Figure 10: Hanscom training site, Day 2, core temperature (T_C) and metabolic rate ($\dot{M}$) (mean ± 1 standard deviation).

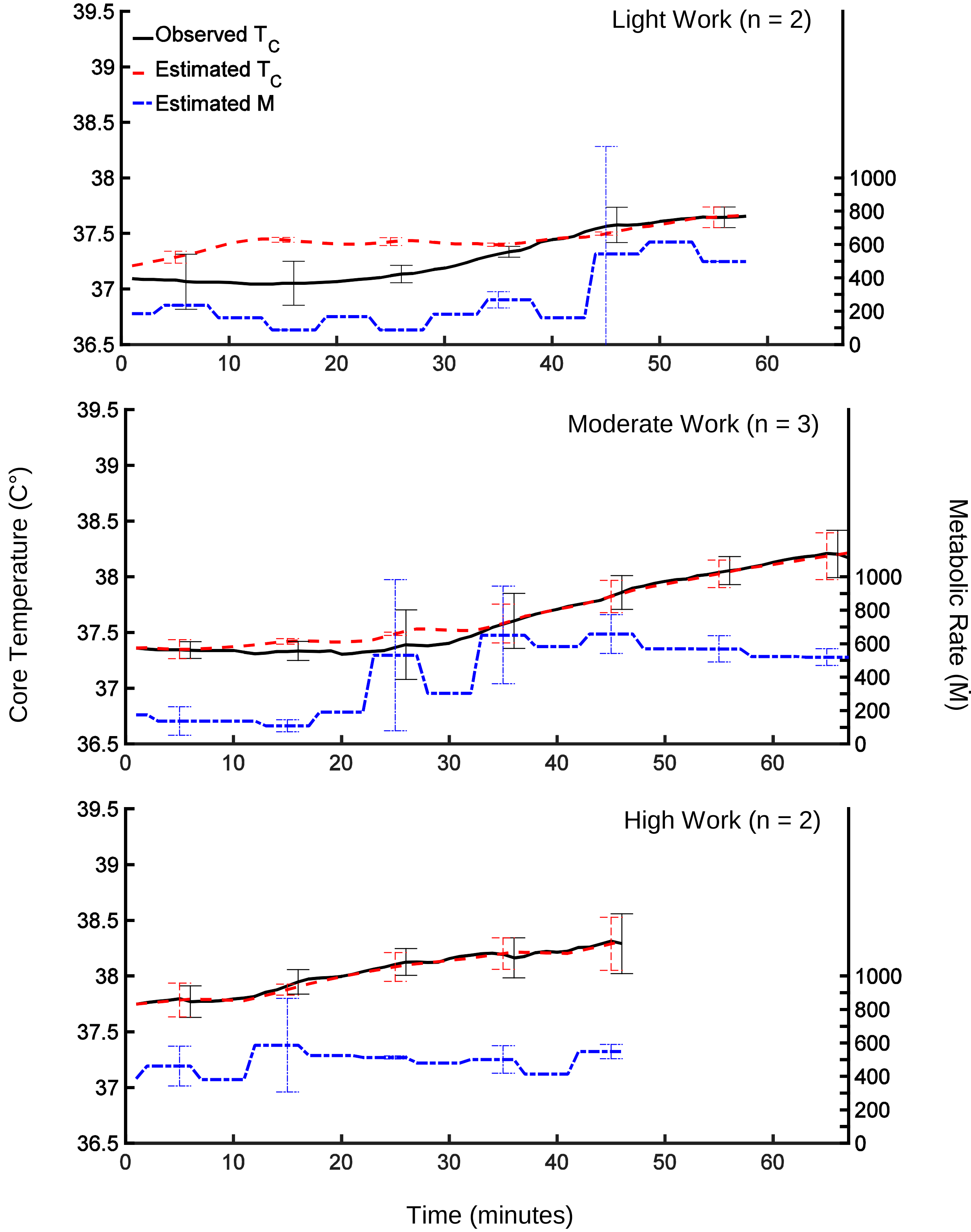
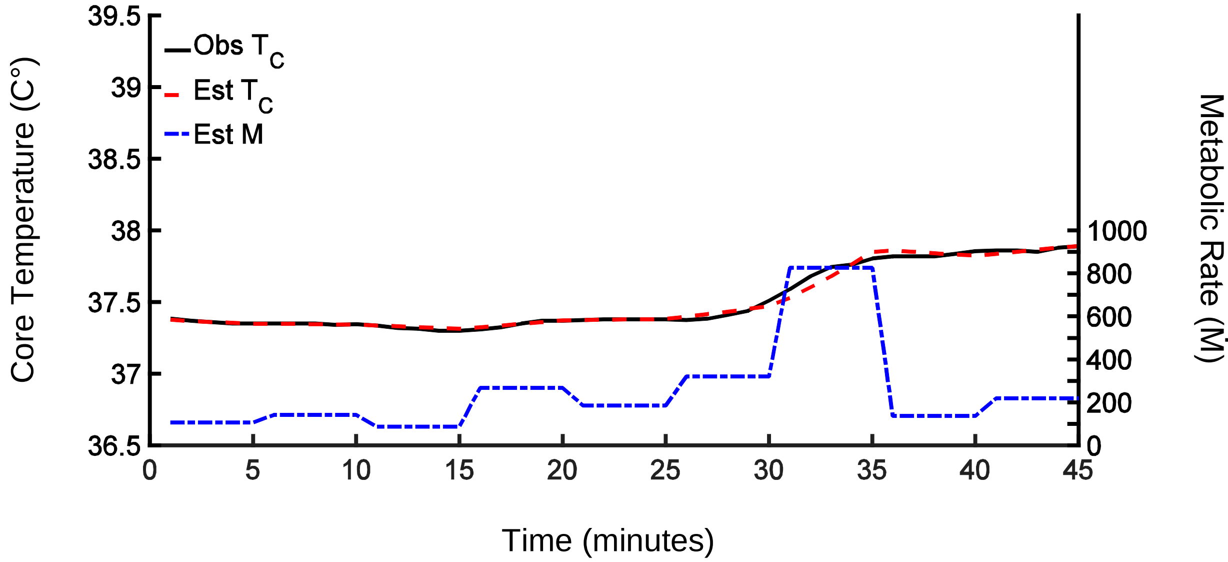


Figure 11: Hayward training site, core temperature (T_C) and estimated metabolic rate ($\dot{M}$) for one volunteer.



DISCUSSION

Estimating $\dot{M}$ profiles for each training period appear to have been successful as RMSE difference between observed and estimated T_C data was minimal with a maximum error of 0.13 °C (Table 2: Hanscom, Days 1 and 2). Furthermore, T_C RMSE values only met or exceeded 0.10 °C for 4 of the 15 exercise bins (e.g., location, day, work intensity). Despite some exercise periods taking place in relatively low air temperatures (e.g., $T_{A\,=}$ ~14 to 21 °C, Table 1; Hayward and Hanscom training locations) and at "light" estimated work intensities (Table 2; < 300 W), mean $\Delta T_{C,max}$ across training periods was 0.8 ± 0.5 °C and ranged between 0.4 ± 0.1 °C and 1.6 ± 0.2 °C. These T_C increases are considerable and, especially given the predominance of "light" and "moderate" work intensities, indicate that the CBRN/E ensembles made it difficult to shed metabolic heat due to their relatively high insulation values and low vapor permeability.

It is also important to note that binning volunteer $\dot{M}$ profiles by mean $\dot{M}$ does not capture low duration periods of high activity. For example, at the Hayward training location on Day 3 one volunteer's $\dot{M}$ reached a maximum value of 861 W while evacuating a casualty down several flights of stairs via sked (Figure 11). This high $\dot{M}$ was not sustained for longer than 5 minutes, nor uniform across volunteers on that day, thus the mean $\dot{M}$ profile (Figure 12) does not capture this individual's spike in $\dot{M}$. Individual $\dot{M}$ profiles for each volunteer are calculated in the process of generating the mean $\dot{M}$ profiles for each training location and day.

The largest RMSE values between observed and estimated T_C are associated with early portions of training periods when a volunteer's initial T_C is very low (Figures 8, 13, 14, and 16). This may suggest why the largest errors (0.8 to 0.13 °C, Table 2) are associated with “light” work intensity periods where SCENARIO cannot match observed T_C values as accurately while volunteers are doing very little to almost no work. Given the constraints of the model inputs (environmental conditions, clothing characteristics, etc.) and the model itself, there is no $\dot{M}$ low enough (including their resting $\dot{M}$) to allow the modeled volunteer to shed heat fast enough to match lower but still valid T_C values (e.g., 36.5 °C). These initial errors may suggest that the accuracy of $\dot{M}$ and T_C estimations can be improved by modifying some of SCENARIO’s internal set points in response to the initial T_C value but, such work is beyond the scope of this work effort.

CONCLUSIONS

Mean metabolic rate and total energy expenditure profiles were estimated for volunteers engaged in CBRN training exercises at three separate locations while encapsulated in either JSLIST MOPP4 or Level A CBRN-PPE. Mean estimated metabolic rates ranged from 184 ± 66 W to 542 ± 142 W while estimated energy expenditure ranged from 1.2 ± 0.2 MJ to 2.6 ± 0.4 MJ.

The estimated metabolic rate, estimated energy expenditure, and observed core temperature data presented in this report may provide benchmarks and metabolic profiles for scientists, materiel developers, and Warfighters to make informed decisions about the metabolic and thermal costs of encapsulating PPE during typical training exercises.

DISCLAIMER

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the Army or the Department of Defense. The investigators have adhered to the policies for protection of human subjects as prescribed in Army Regulation 70-25 and SECNAVINST 3900.39D, and the research was conducted in adherence with the provisions of 32 CFR Part 219. Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

REFERENCES

1. ASTM Standard F1291-10: Standard Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin. West Conshohocken, PA, ASTM International, 2010.

2. ASTM Standard F1868-09: Standard Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot plate. West Conshohocken, PA, ASTM International, 2009.

3. Dorman LE and Havenith G (2008). The effects of protective clothing on energy consumption during different activities. *Eur J Appl Physiol*, 105:463-470.

4. Goetz V, Yokota M, Karis AJ, and Tharion WJ (2011). Energy expenditure and metabolic heat production storage estimates of tactical law enforcement personnel during chemical, biological, radiological, and nuclear (CBRN) training. Technical Report T11-05 (ADA549510). Natick, MA: U.S. Army Research Institute of Environmental Medicine. http://www.dtic.mil/get-tr-doc/pdf?AD=ADA549510

5. Kranning KK and Gonzalez RR (1997). A mechanistic computer simulation of human work in heat that accounts for physical and physiological effects of clothing, aerobic fitness, and progressive dehydration. *Journal of Thermal Biology*, 22(4): 331-2.

6. Mifflin MD, St. Jeor ST, Hill LA, Scott BJ, Daugherty SA, and Koh YO (1990). A new predictive equation for resting energy expenditure in health individuals. *The American Journal of Clinical Nutrition*, 51(2):241-247.

7. Montoye HI, Kemper HC, Saris WH, and Washburn RA (1996). *Measuring physical activity and energy expenditure*. Champaign, IL: Human Kinetics.

8. Muza SR, Banderet LE, and Cadarette B (2001). Protective Uniforms for Nuclear, Biological, and Chemical Warfare. In *Medical Aspects of Harsh Environments*, Chap. 36 edited by Pandolf KB and Burr RE, 1084-1127. Falls Church VA: Office of the Surgeon General, United States Army.

9. Potter AW, Gonzalez JA, Karis AJ, Blanchard LA, Rioux TP, and Santee WR (2015). Biophysical characteristics of chemical protective ensembles with and without body armor. Technical Report T15-8 (ADA621169). Natick, MA: U.S. Army Research Institute of Environmental Medicine. http://www.dtic.mil/get-tr-doc/pdf?AD=ADA621169

10. Potter AW, Gonzalez JA, and Xu X (2015). Ebola Response: Modeling the Risk of Heat Stress from Personal Protective Clothing. *PLoS One*, 10(11), e0143461.

11. Sawka MN and Pandolf KB (2001). Physical exercise in hot climates: physiology, performance, and biomedical issues*.* Medical aspects of harsh environments volume 1, pp 93.

12. Sawka MN, Wenger CB, Montain SJ, Kolka MA, Bettencourt B, Flinn S, Gardner J, Matthew WT, Lovell M, and Scott C (2003). Heat stress control and heat casualty management Technical Bulletin MED 507 (ADA433236). Natick, MA: US Army Research Institute of Environmental Medicine. http://www.dtic.mil/get-tr-doc/pdf?AD=ADA433236

13. USARIEM: SCENARIO – Human Thermoregulatory Response Model (2016, SEP 14). Retrieved from http://www.usariem.army.mil/index.cfm/modeling/scenario

14. Welles AP, Buller MJ, Richter MW, McCarthy S, and Hoyt RW (2015). Thermal-work Strain and Energy Expenditure During Marine Rifle Squad Operations in Afghanistan (AUGUST 2015). Technical Report T15-7 (ADA620719). Natick, MA: U.S. Army Research Institute of environmental Medicine. http://www.dtic.mil/dtic/tr/fulltext/u2/a620619.pdf

APPENDIX A

ESTIMATED 5 MINUTE INTERVAL METABOLIC PROFILES

Edgewood Metabolic Profiles (Watts, 5 minute intervals)			
Day 1		Day 2	
Low	Moderate	Low	Moderate
127	295	87	263
143	302	142	303
174	257	168	251
174	252	172	251
170	242	177	239
278	235	183	212
165	327	87	175
293	259	264	234
184	292	498	253
224	260	102	244
170	329	161	242
152	501	140	174
256	302	236	131
210	236	294	149
213	286	174	151
265	336	229	140
323	302	140	262
279	223	119	141
247		192	341
257		200	405
218		237	427
269		257	462
240		331	533
281		308	506
279		198	438
274		425	508
263		326	412
284		555	398
		391	
		432	

Hanscom Metabolic Profiles (Watts, 5 minute intervals)					
Day 1			Day 2		
Low	Moderate	High	Low	Moderate	High
106	100	529	123	138	416
114	127	429	135	426	422
139	115	432	186	156	396
156	143	415	199	192	393
234	160	455	185	175	387
150	267	497	235	137	461
103	108	650	160	136	381
200	87	486	87	108	586
211	123	525	168	190	524
136	188	585	87	531	513
87	616	486	182	303	480
238	836	435	268	651	501
604	643	534	160	583	413
614	544	528	544	658	548
473	598	481	615	569	
375	493		499	568	
	530			522	
				519	

Hayward Metabolic Profiles (Watts, 5 minute intervals)				
Day 1			Day 2	Day 3
Low	Moderate	High	Low	Low
128	128	453	114	87
145	146	302	129	151
175	236	319	188	163
160	233	315	206	166
176	233	317	364	166
168	87	405	116	387
184	87	371	161	131
149	87	377	114	130
210	269	504	281	141
185	233	571	137	169
100	87	635	252	285
138	117	645	226	119
218	942	717	193	163
186	620	686	140	191
88	751	723	111	193
315	756	488	152	237
556			123	231
602			233	194
731			161	157
463			133	164
			209	213
			160	239
			181	378
			169	189
			147	182
			213	